RCA PU030262 Ref AD

CITED BY APPLICANT

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 174 998 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
23.01.2002 Bulletin 2002/04

(51) Int Cl.[7]: **H02P 6/08**, H02P 6/14, H02M 1/00

(21) Application number: **00830433.9**

(22) Date of filing: **21.07.2000**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE
Designated Extension States:
AL LT LV MK RO SI

(71) Applicant: **MAGNETEK S.p.A.**
52028 Terranuova Bracciolini (AR) (IT)

(72) Inventors:
- **Canova, Antonio**
  52025 Montevarchi,Arezzo (IT)
- **Bianchi, Andrea**
  52028 S. Giovanni Valdarno,Arezzo (IT)

(74) Representative:
Mannucci, Gianfranco, Dott.-Ing. et al
Ufficio Tecnico Ing. A. Mannucci Via della Scala 4
50123 Firenze (IT)

(54) **Brushless motor,method and circuit for its control**

(57) The control circuit for brushless motors comprises a power supply inverter (7) for supplying the motor; a rectifier bridge (3); a smoothing section (6) placed between the rectifier bridge (3) and the power supply inverter (7). The smoothing section comprises at least two capacitors (C1, C2) and control means (D1, D2, Q1) for modifying the connections of said capacitors.

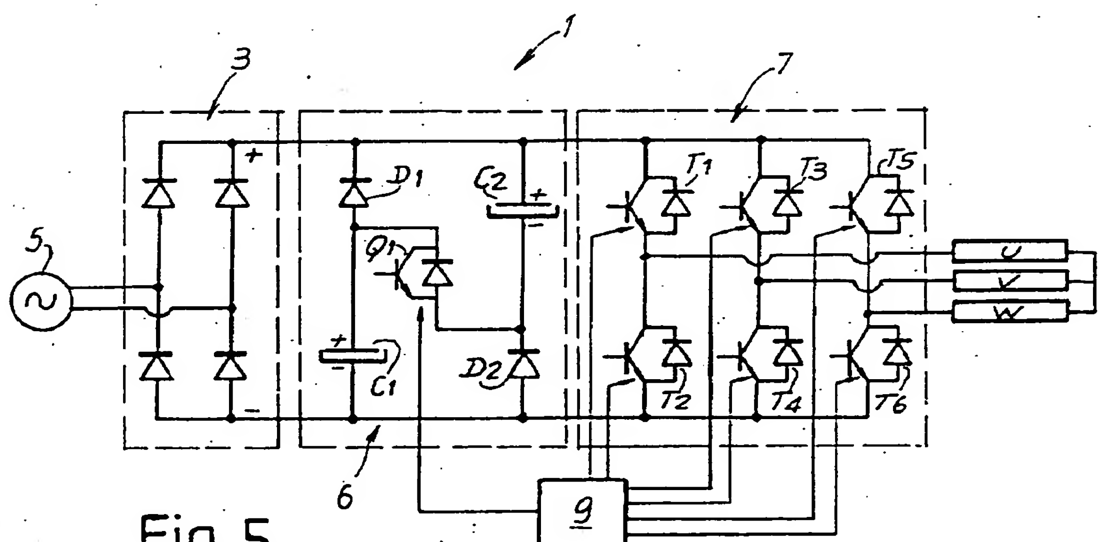

Fig. 5

REF. 5 DOCKET PU030262
CORRES. COUNTRY:
COUNTRY: PCT

EP 1 174 998 A1

Description

[0001] The present invention relates to a method and circuit for the control of the supply of a "brushless" motor, especially for a trapezoidal brushless motor.

[0002] The invention also relates to a motor equipped with said circuit.

[0003] A trapezoidal brushless motor is a synchronous motor consisting of a rotor, on which permanent magnets are fitted, and a stator on which there is a star-connected three-phase winding. The description "brushless DC" (direct current motor without brushes) is based on its operating principle, which is conceptually similar to that of a direct current motor.

[0004] A direct current motor has a permanent magnet on the stator and the windings on the rotor. The rotation is obtained by appropriately switching the polarity of the magnetic field produced by the windings according to the position of the rotor. This is done by means of suitable brushes which electrically connect the windings (on the rotor) to the direct current source.

[0005] Unlike a direct current motor, a brushless motor has the permanent magnet on the rotor and the windings on the stator. The rotation is obtained by appropriately switching the polarity of the magnetic field produced by the windings according to the position of the permanent magnets on the rotor. The switching of the windings is carried out by means of an electronic converter. If made to rotate, the brushless motor acts as a generator; the voltages obtained, between a phase and the center of the star, are of trapezoidal form (from which the name is derived). Its peak value is directly proportional to the velocity of rotation according to the following relation:

$$Vpk = K_E \cdot N$$

where

N is the number of revolutions per minute
K_E is a constant which depends on the motor.

[0006] These induced voltages appear independently of the cause of the rotation of the motor, and therefore also during operation as a motor, and are called back electromotive forces (Vbemf).

[0007] Trapezoidal brushless motors are frequently controlled by setting a constant current in the two active phases, without control of the third phase. The correct sequence of the active phases enables the motor to rotate in the desired direction of rotation.

[0008] To keep the phase current constant, the active phases are controlled by means of an inverter comprising electronic switches arranged in the form of a three-phase full bridge. The system is supplied with a continuous voltage. This can be obtained either by means of a battery or directly from the mains by means of an AC-DC converter. The typical layout for a mains supply to the system comprises a diode bridge and a smoothing capacitor of suitable sizes. Fig. 1 shows schematically a control circuit, with an inverter for supplying the three phases, indicated by u, v and w, of the motor. The inverter comprises six controlled electronic switches, indicated by T1-T6. A continuous voltage Vc, which is present across a smoothing capacitor C connected in parallel to a diode rectifier bridge D, is supplied to the three-phase bridge formed by the switches T1-T6.

[0009] Fig. 2 shows schematically the polarities of the permanent magnet of the rotor and the three phases u, v, w forming the stator windings. Fig. 3 shows schematically the currents I_u, I_v, I_w on the three phases as a function of the electrical angle, shown on the horizontal axis. It also shows which of the switches T1-T6 are closed (ON) for each interval of 60 electrical degrees (indicated by A-F). In the diagram, the rising and descending current ramps have been omitted for the sake of simplicity, an instantaneous switching of the current being assumed.

[0010] Between two successive switchings, the phase current has to remain within a tolerance range (in other words, the lower and upper values are fixed). To achieve this, the electronic switches T1-T6 of the three-phase bridge are operated in such a way that all the voltage available at the output of the rectifier bridge is present across the active phases with a suitable sign. In particular, when the current has to rise, the active phase is supplied with a positive sign, and the current increases with a slope determined by:

$$\frac{dI}{dt} = \frac{Vdc - Vbemf}{Lmot}$$

[0011] As soon as the value of the current has reached the upper limit set, the electronic switches are switched, and the active phase is supplied with a negative sign. The current decreases with a slope determined by:

$$\frac{dI}{dt} = \frac{-Vdc - Vbemf}{Lmot}$$

[0012] The current passes through the diodes and the smoothing capacitor is charged.

[0013] This configuration is maintained until the current reaches the lower limit, after which the initial configuration is restored and the current starts to increase again.

[0014] As can be deduced from the above, the switching of the phases causes stepwise variations of the currents of the phases u, v and w of the motor (Fig. 3). Because of the back electromotive force generated in the individual windings by the rotation of the motor, the supply voltage must be sufficiently greater than the back electromotive force if rapid switching is to be obtained. This means that it is sufficient to have a lower value of

continuous voltage when the number of revolutions is low than when the rotation is fast. On the other hand, the high voltage is required only during the stages of switching the phase current, and is not required when there is no switching of current in the phases of the motor.

[0015] In conventional control circuits, there is a large variation of the current drawn from the mains during the electrical period, which is manifested in a reduction of the power factor. The current I_C in the capacitor C and the current I_D supplied by the diode bridge have a variation characterized by a marked peak, as shown in the diagram in Fig. 4, which represents the variation of I_D and I_C as a function of time. The same diagram also shows the variation of the voltage V_C across the capacitor C.

[0016] In addition to a limited power factor, the circuits used at present for controlling brushless motors have a relatively high r.m.s. (root-mean-square) value of current absorption, making it necessary to use large-sized and expensive components for the input filter and for the rectifier bridge. Additionally, the smoothing capacitor has to be capable of reaching high voltages, equal to the peak voltage of the power supply.

[0017] The object of the present invention is to provide a control circuit for brushless motors and a corresponding method which make it possible, on one hand, to improve the power factor, and, on the other hand, to reduce the cost of the circuit components.

[0018] A further object of the present invention is to provide a less expensive circuit.

[0019] These and further objects and advantages, which will be clearly understood by a person skilled in the art from the following text, are essentially achieved with a control circuit in which a smoothing section, comprising at least two capacitors and control means which modify the conditions of interconnection of the two capacitors, is interposed between the rectifier bridge and the power supply inverter.

[0020] The control means can advantageously comprise a controlled electronic switch, for example a transistor.

[0021] The control means and the capacitors are made and connected, in a possible embodiment of the invention, in such a way that, by the operation of the control means, the two capacitors can be connected alternately in series and in parallel to modify the supply voltage according to the actual demand across the three-phase bridge.

[0022] With this arrangement, each capacitor has to withstand not more than half of the peak voltage. It is therefore possible to use less expensive components. For a given capacitance, the total cost of the two capacitors, of the 200 V electrolytic type for example, is less than the cost of a 400 V capacitor of the snap-in type. Moreover, as will be shown subsequently, when the motor rotates at a sufficiently low velocity, a consistent improvement in the power factor is also obtained.

[0023] Further advantageous characteristics of the circuit according to the invention and of the corresponding method are shown in the attached claims.

[0024] The invention will be more clearly understood from the description and the attached drawing, which shows a practical and non-restrictive embodiment of the circuit according to the invention. In the drawing,

- Figs 1 to 4 show the circuit layout, the schematic diagram of the motor, the variation of the currents in the three phases and the variation of the currents in the capacitor and in the diode bridge in the conventional circuit, as described in a summary way above;
- Fig. 5 shows schematically the control circuit according to the invention;
- Fig. 6 shows the circuit equivalent to that of Fig. 5, where the power supply inverter and the three phases of the stator winding have been replaced by an equivalent constant current source;
- Figs 7A-7D show the various stages of operation of the circuit;
- Figs 8 and 9 show the variation of the currents and voltages in the circuit, in two diagrams on different scales; and
- Fig. 10 shows a modified embodiment of the circuit.

[0025] Fig. 5 shows schematically the control circuit according to the invention, indicated in a general way by 1. The number 3 indicates a diode rectifier bridge, connected to an alternating voltage source 5. The number 6 indicates in a general way a smoothing section, which comprises two smoothing capacitors C1 and C2. The first capacitor C1 has a first electrode connected through a first diode D1 to the positive pole of the rectifier bridge 3, while the other electrode is connected to the negative pole of the rectifier bridge 3. Conversely, the second capacitor C2 has one of its electrodes connected to the positive pole of the rectifier bridge and the other electrode connected through a diode D2 to the negative pole of the bridge 3.

[0026] The two capacitors C1, C2 are connected together through an electronic switch Q1, which connects the negative electrode of the capacitor C2 to the positive electrode of the capacitor C1.

[0027] The number 7 indicates the power supply inverter, which has six electronic switches T1-T6 in a three-phase bridge configuration, each of these being controlled in a known way by a programmable control unit indicated schematically by 9. This unit also controls the switching of the electronic switch Q1 in the way described below.

[0028] Since the motor is supplied with a constant current, the current at the input of the three-phase bridge 7 is constant. In suitable conditions, the three-phase bridge can be considered as a theoretical constant current generator. The equivalent layout becomes that shown in Fig. 6, where identical numbers indicate parts

identical or equivalent to those of the circuit of Fig. 5.

[0029] The illustrated circuit operates as follows. The stages of operation are shown schematically in Figs 7A-7D. Let us assume that the power supply voltage supplied by the source 5 is sinusoidal and of amplitude Vo.

[0030] Let us suppose that the switch Q1 is initially in the OFF state. Because of the diode in antiparallel with Q1, the capacitors C1 and C2 are connected in series with each other, and each of them is charged to a value close to Vo/2. In static conditions, the charging takes place in the proximity of the maximum absolute value of the power supply voltage upstream of the diode bridge 3, and this causes a pulse of current absorbed by the diodes of the bridge 3. This situation is shown in Fig. 7A, where the current I_D, part of which is supplied to the load (current I) and part of which (current I_C) charges the capacitors C1, C2, is supplied through the diode bridge 3.

[0031] As soon as the rectified input voltage V_x becomes less than the sum of the voltages across the capacitors C1 and C2, the charging pulse of the capacitors is exhausted (I_C becomes equal to zero), and since the two diodes D1 and D2 are polarized inversely, the capacitors C1 and C2 cannot supply power to the load. The diodes of the rectifier bridge 3 are kept conducting by the motor current (represented by the theoretical generator of current I) and the current I_D drawn from the mains is constant and coincides with that set by the motor (I_D = I). The situation is shown in Fig. 7B.

[0032] When the input voltage V_x takes an absolute value of less than Vo/2, the diodes of the bridge 3 cease to conduct. The diodes D1 and D2 are polarized directly and conduct. Consequently, the capacitors C1 and C2 supply power to the load, each contributing approximately half of the load current I. The voltage across the current generator which represents the three-phase bridge supplying the motor phases is stabilized at approximately Vo/2, and the capacitors C1 and C2 are in parallel with each other. The situation is that shown in Fig. 7C.

[0033] Conversely, when the switch Q1 is closed (ON) the diode D1 is in parallel with the capacitor C2 and the diode D2 is in parallel with the capacitor C1. Both the diodes D1 and D2 are polarized inversely, and the two capacitors C1 and C2 are in series with each other and supply the current I_C = I to the load. The voltage across the load is approximately Vo. This situation is shown in Fig. 7D.

[0034] Clearly, whenever Q1 is closed, the voltage across the load tends toward a value close to Vo, independently of the value previously taken.

[0035] Therefore, by suitably controlling the instants of conduction of the switch Q1, the capacitors C1 and C2 can be connected in series with each other to supply the voltage Vo to the three-phase bridge, and consequently to the load, although the two capacitors C1, C2 are at a voltage of not more than Vo/2.

[0036] With reference to the schematic diagram of Fig. 3, the voltage across the three-phase bridge can remain at a low level, typically equal to Vo/2 during the operation at constant current and brought to the value Vo during the rising fronts of the current. Therefore, the switch Q1 is controlled by the unit 9 in such a way that it is closed when the rising fronts of the current appear in one of the three phases of the motor, provided that the supply voltage across the rectifier bridge 3 is not already sufficiently high. In this case, the closing pulse of the switch Q1 can be suppressed.

[0037] Fig. 8 shows the variation with time of the voltage (V_x) across the inverter, in other words across the three-phase bridge 7, together with the variation of the current (I_D) drawn from the mains and the current (I_C) to the capacitors C1, C2. The diagram shows two peaks of absorption of current (I_D) from the mains, coinciding with the stage of charging of the two capacitors C1, C2, which are in series at this instant. Between two successive stages of charging of the capacitors C1, C2, three voltage peaks, each lasting for a time T_{on}, can be identified. These voltage peaks are obtained by the closing of the switch Q1 for the time interval T_{on}. As shown in the diagram of Fig. 8, the voltage V_x which is thus applied to the load is approximately equal to Vo, although it tends to decrease slowly because of the progressive discharging of the capacitors. The rising fronts of the current in one of the phases u, v and w of the motor are located in the intervals T_{on}. When a rising front of the current is located temporally in a stage in which the circuit is in the configuration shown in Fig. 7A, the closing command to the switch Q1 is suppressed, since the capacitors C1, C2 are already in series with each other and supply a voltage sufficiently close to Vo. In the diagram of Fig. 8, the references 7A-7D indicate the areas of the diagram corresponding to the operating conditions illustrated in Figs 7A-7D respectively, for ease of comparison between the variation of the curves of Fig. 8 with the state of the circuit components as a function of time.

[0038] The diagram of Fig. 8 uses a time scale which is expanded with respect to that of the diagram of Fig. 4, for easier reading. Fig. 9 reproduces the diagram of Fig. 8, but with the time scale used in Fig. 4 on its horizontal axis. This makes it possible to determine, by direct comparison of the two diagrams, the effect obtained by the division of the smoothing capacity between the two capacitors C1, C2, and by the control of the switch Q1; the peak of current drawn from the mains is very small, with consequent advantages in terms of the power factor.

[0039] The above analysis of the behavior of the circuit of Fig. 5 is true for a condition in which motor rotation velocities are not very high. In this condition, high voltages are required only when the active phase of the motor has to be changed (six times in one electrical period). Consequently, the switch Q1 will be made to conduct only in these cases, and will remain in this state only for the time necessary for the phase current to adjust its value. It has also been remarked above that the con-

duction interval of the switch Q1 can be eliminated if the input voltage is sufficiently high. In order to further improve the power factor, the motor can be synchronized, when it rotates at constant velocity, with the mains voltage.

[0040] In some applications it is useful to be able to obtain very high speeds for brief periods. To do this, it is necessary to keep the switch Q1 continuously conducting, in other words to keep the capacitors C1 and C2 always in series. In this way, the benefits in terms of the power factor are lost, but not those related to the savings due to the cost of the components.

[0041] Fig. 10 shows a different embodiment of the circuit, in which a rectifier bridge 3 of the three-phase type is provided. In this case, the smoothing section 6 can again comprise two capacitors C1 and C2, connected, by means of two corresponding electrodes, to a controlled switch, again indicated by Q1. The other electrodes are connected to the positive pole and to the negative pole of the rectifier bridge 3. In this case, owing to the waveform of the output voltage of the three-phase rectifier bridge, it is not necessary to connect the capacitors alternately in series and in parallel. They will be connected in series when a high rotation velocity of the motor is required, by making the controlled switch Q1 conduct. When the operating frequency is lower, the two capacitors can be brought into the floating condition, in other words with the controlled switch Q1 in the "off" state.

[0042] Fig. 10 also shows a braking circuit of a known type, indicated in a general way by 21 and comprising a dissipation resistance in series with a second controlled switch Q2. This is closed to dissipate to the resistance the current generated by the motor in the braking phase. In the braking phase, also the controlled switch Q1 of the smoothing section 6 will be conducting.

[0043] The braking circuit can also be provided in the configuration of the preceding figures.

Claims

1. A control circuit for brushless motors, comprising:

   - a power supply inverter (7) for supplying the motor;
   - a rectifier bridge (3);
   - a smoothing section (6) placed between the rectifier bridge (3) and the power supply inverter (7),

   characterized in that said smoothing section comprises at least two capacitors (C1, C2) and control means (D1, D2, Q1) for modifying the connections of said capacitors.

2. The circuit as claimed in claim 1, in which said control means comprise at least one controlled switch (Q1).

3. The circuit as claimed in claim 1 or 2, in which said control means (D1, D2, Q1) can bring said two capacitors alternately into connection in series and in parallel with each other.

4. The circuit as claimed in claim 1 or 2, in which said rectifier bridge (3) is a three-phase bridge and in which said control means (Q1) are placed between an electrode of a first of said capacitors (C1, C2) and an electrode of a second of said capacitors, and bring said capacitors alternately into connection in series with each other and into isolation from each other.

5. The circuit as claimed in one or more of the preceding claims, in which said power supply inverter (7) comprises a bridge of controlled switches (T1-T6).

6. The circuit as claimed in claim 5, in which said bridge of controlled switches is a three-phase bridge.

7. The circuit as claimed in one or more of the preceding claims, in which:

   - a first (C1) of said capacitors is connected by one electrode to the negative pole of the rectifier bridge and by the other electrode to the positive pole of the rectifier bridge (3) by means of a first diode (D1);
   - a second (C2) of said capacitors is connected by one electrode to the positive pole of the rectifier bridge (3) and by the other electrode to the negative pole of said rectifier bridge by means of a second diode (D2).

8. The circuit as claimed in claim 7, in which said control means comprise a controlled electronic switch (Q1) of which one end is connected between the first capacitor (C1) and the first diode (D1) and the other end is connected between the second capacitor (C2) and the second diode (D2).

9. The circuit as claimed in one or more of the preceding claims, in which said control means bring said capacitors (C1 and C2) into connection in series when the inverter has to receive an input voltage higher than that which is available on the rectifier bridge and which can be supplied by the capacitors in parallel.

10. The circuit as claimed in claim 9, in which said control means bring the capacitors into connection in series during the stages of switching the windings of the brushless motor, if the voltage across the rectifier bridge (3) is lower than a threshold value.

11. The circuit as claimed in one or more of the preceding claims, comprising means (21) for braking the motor, with a second controlled switch (Q2), said second controlled switch being closed to obtain the braking of the motor.

12. The circuit as claimed in claim 11, in which during the braking of the motor said first and said second controlled switches (Q1, Q2) are simultaneously conducting.

13. A brushless motor comprising a control circuit as claimed in one or more of claims 1 to 12.

14. The motor as claimed in claim 7, in which said motor is a trapezoidal brushless motor.

15. A method for controlling a brushless motor, comprising the stages of:

- generating a continuous supply voltage by means of a rectifier bridge (3) and a smoothing section (1) comprising at least one capacitor;
- supplying the windings of the motor by means of an inverter (7) connected to said smoothing section;

<u>**characterized in that**</u> the output voltage of said smoothing section is modified as a function of the operating conditions of the motor.

16. The method as claimed in claim 15, **characterized in that** at least two capacitors (C1, C2) are provided in said smoothing section and **in that** their connection is modified by means of a controlled switch (Q1) as a function of the operating conditions of the motor.

17. The method as claimed in claim 15 or 16, **characterized in that** the output voltage of said smoothing section is increased during the stages of switching the motor windings.

18. The method as claimed in claim 15, 16 or 17, **characterized in that** at least two capacitors (C1, C2) are provided in said smoothing section and **in that** said capacitors are connected alternately in series and in parallel with each other.

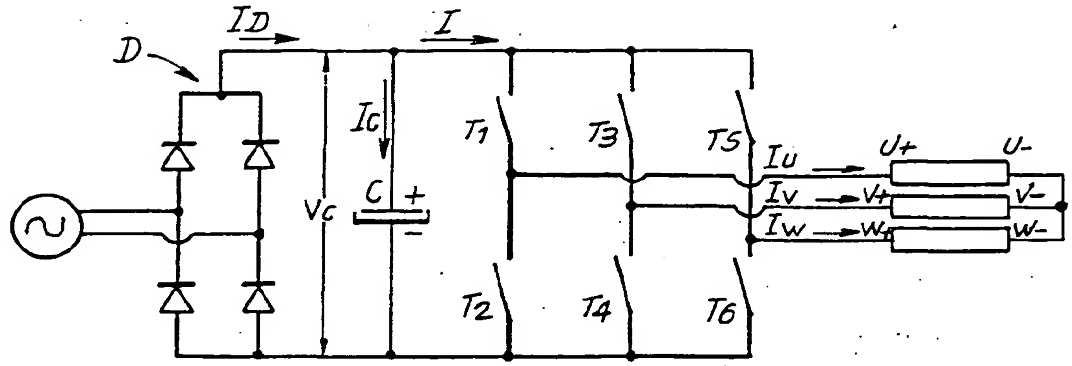

Fig. 1

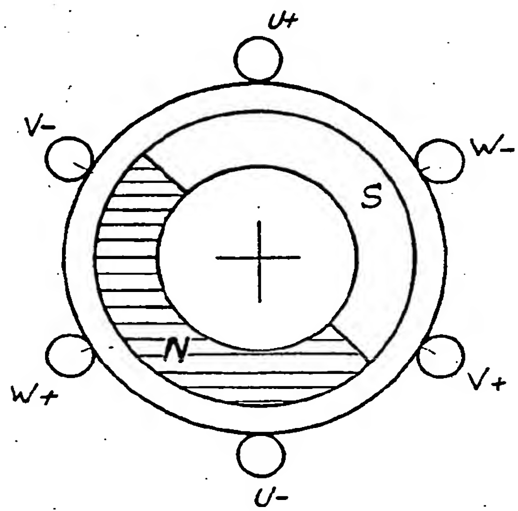

Fig. 2

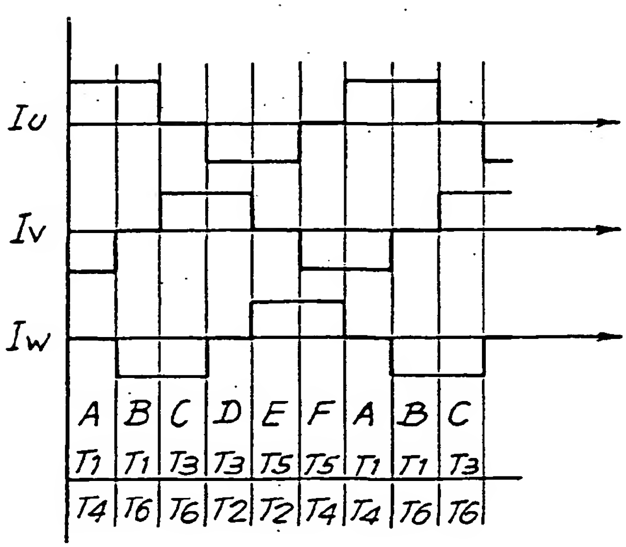

Fig. 3

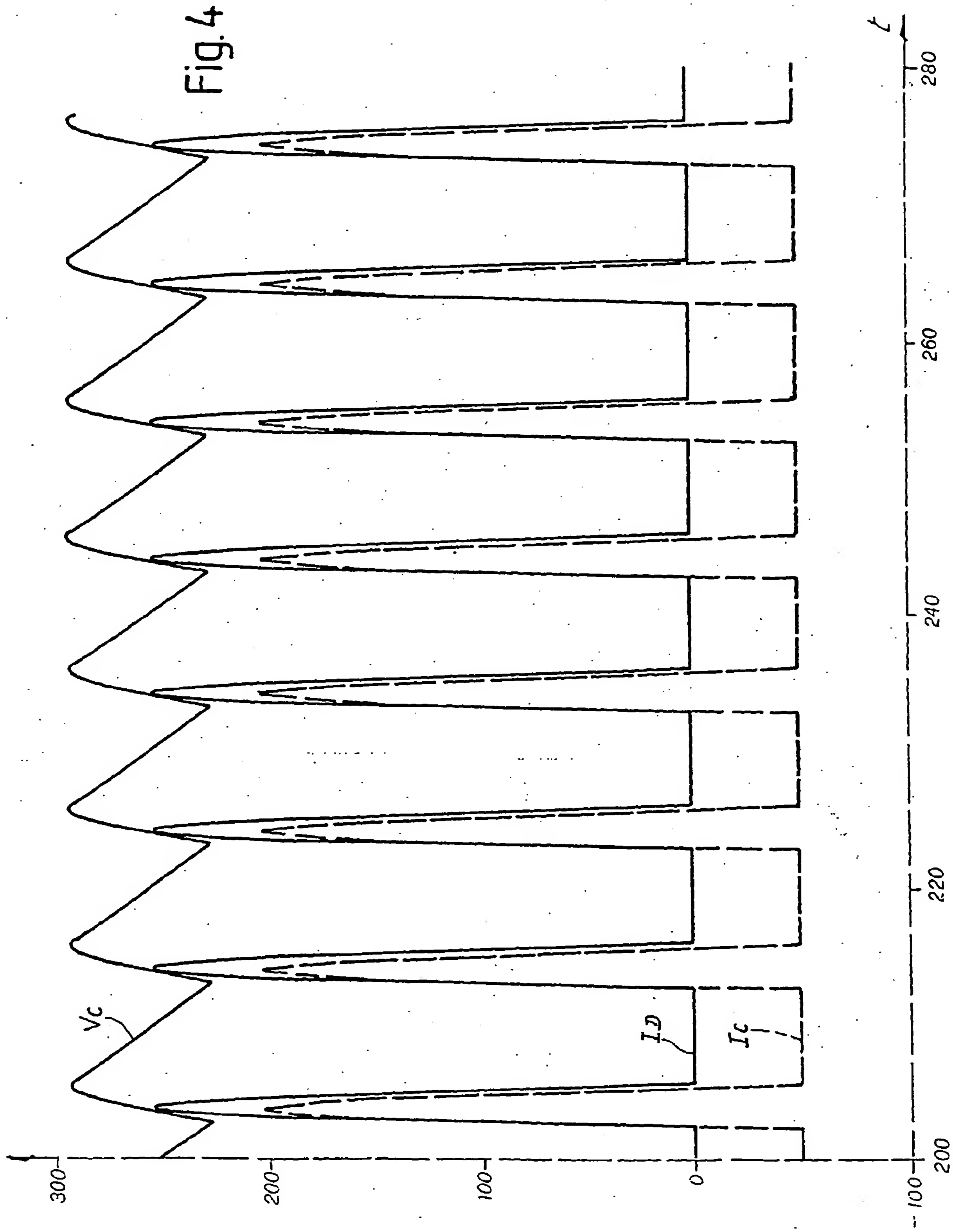

Fig. 4

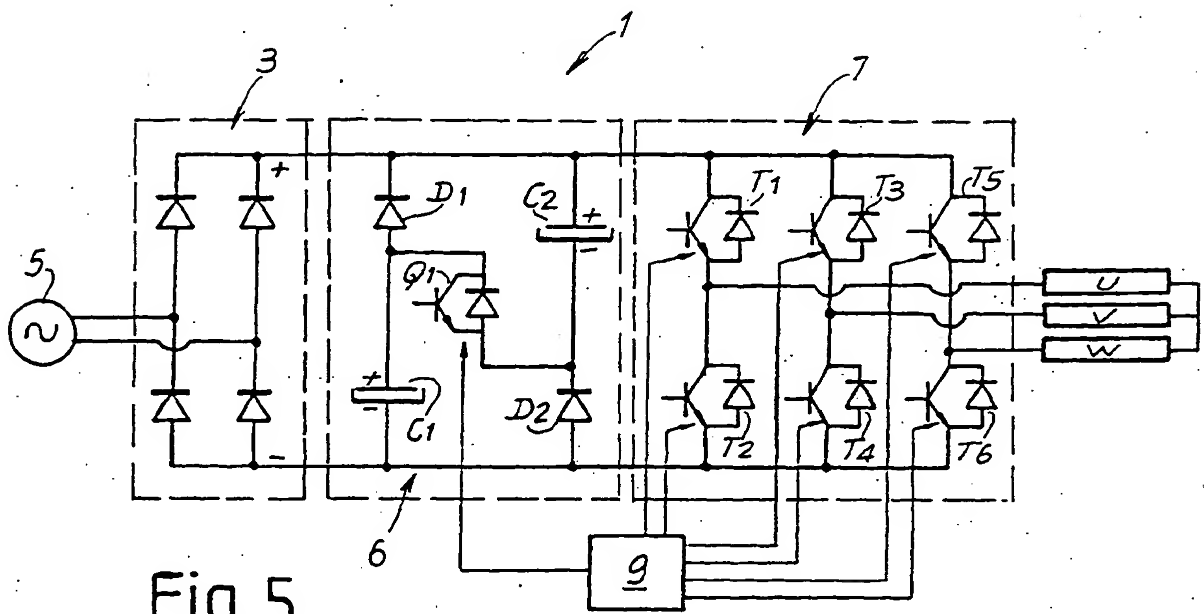
1
3
7
5
+
D1
C2
+
T1
T3
T5
Q1
U
V
W
+
C1
D2
T2
T4
T6
6
9

Fig. 5

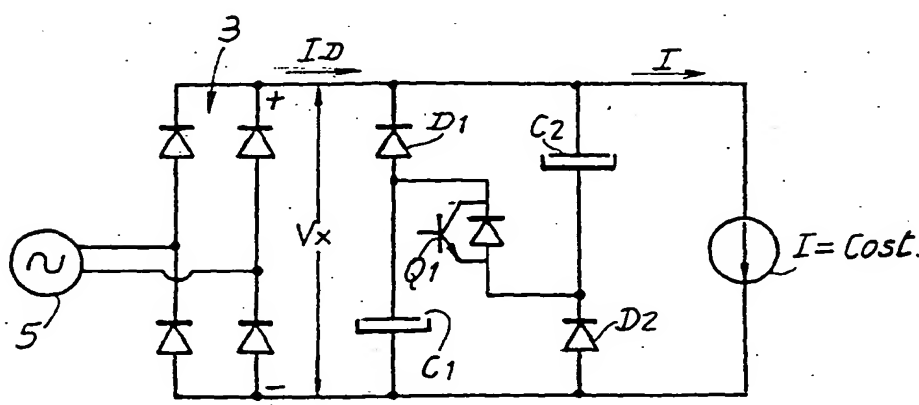
3
ID
I
+
D1
C2
Vx
Q1
I= Cost.
5
D2
C1

Fig. 6

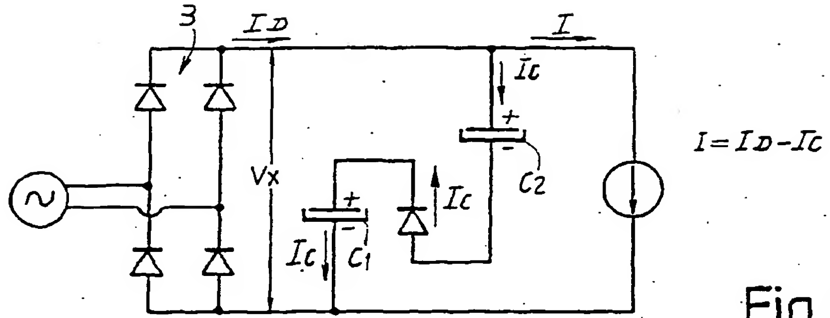

Fig. 7A

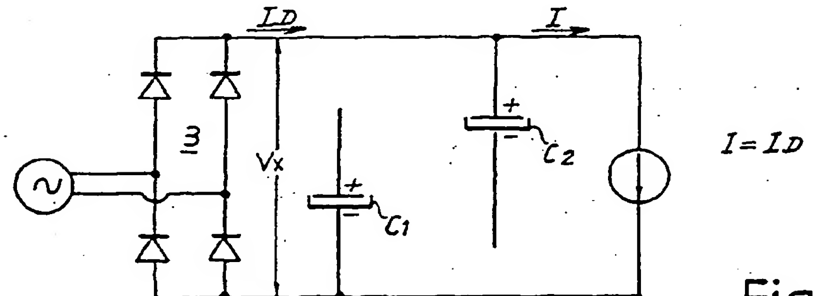

Fig. 7B

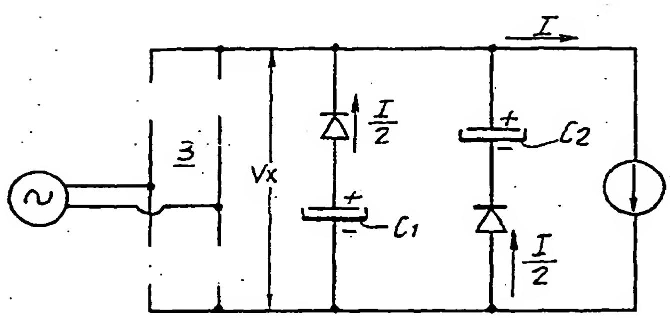

Fig. 7C

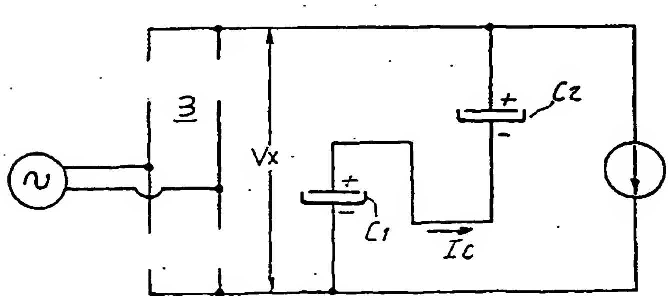

Fig. 7D

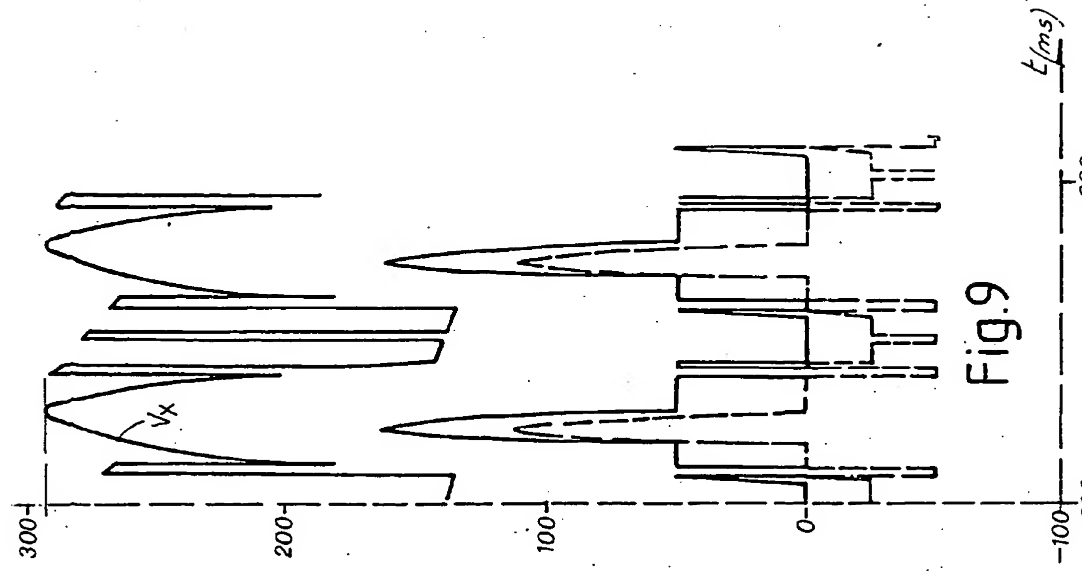
300
200
100
0
-100
200
220
t(ms)
Vx

Fig.9

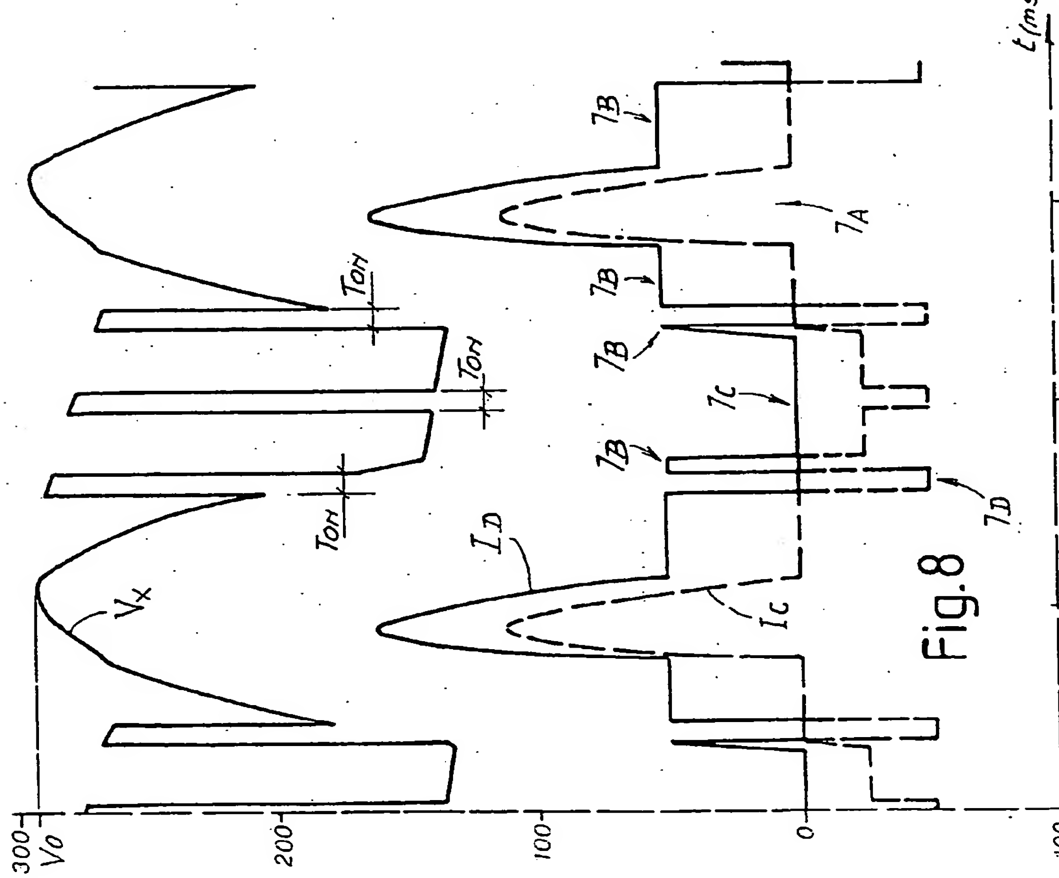
300
Vo
200
100
0
- 100
260
265
270
275
t(ms)
Vx
Ton
ID
Ic
7B
7C
7D
7A

Fig.8

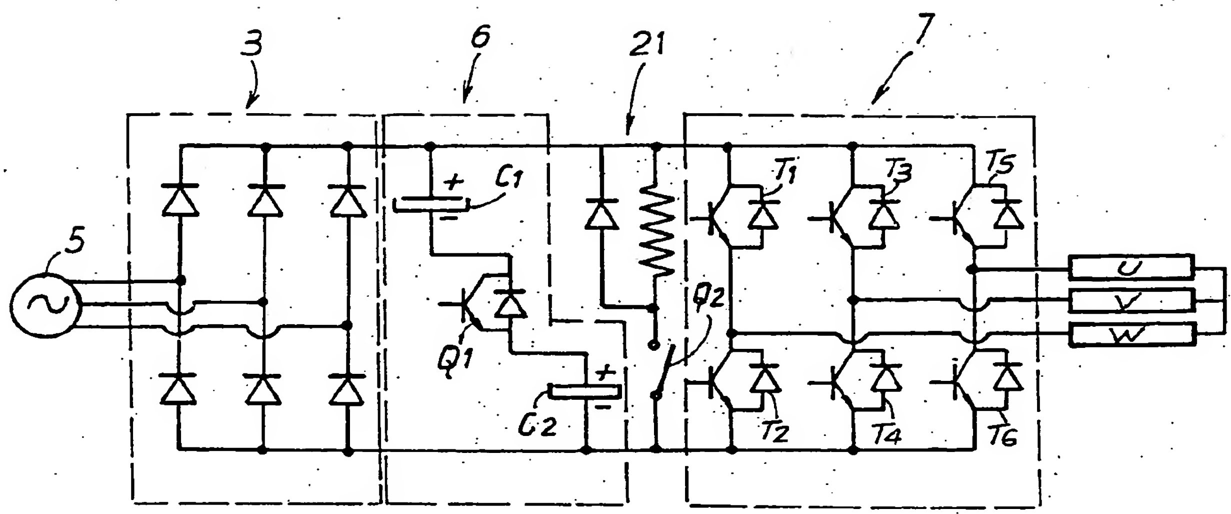

Fig. 10

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 00 83 0433

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
Y	PATENT ABSTRACTS OF JAPAN vol. 017, no. 608 (E-1457), 9 November 1993 (1993-11-09) & JP 05 184188 A (HITACHI LTD;OTHERS: 01), 23 July 1993 (1993-07-23) * abstract *	1,4-6, 13,15,16	H02P6/08 H02P6/14 H02M1/00
Y	US 5 764 037 A (JACOBS MARK ELLIOTT ET AL) 9 June 1998 (1998-06-09) * abstract; figures 2,3 *	1,4-6, 13,15,16	
A	US 6 046 922 A (MOREAU JEAN-MICHEL) 4 April 2000 (2000-04-04) * abstract; figure 4A *	1,13,15	
A	PATENT ABSTRACTS OF JAPAN vol. 012, no. 101 (E-595), 2 April 1988 (1988-04-02) & JP 62 233069 A (MITSUBISHI ELECTRIC CORP), 13 October 1987 (1987-10-13) * abstract *	1,13,15	

TECHNICAL FIELDS SEARCHED (Int.Cl.7)
H02P H02M

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	19 December 2000	Beyer, F

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 00 83 0433

This annex lists the patent family membersrelating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

19-12-2000

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 05184188 A	23-07-1993	NONE	
US 5764037 A	09-06-1998	US 5627455 A	06-05-1997
		EP 0714160 A	29-05-1996
		JP 8242536 A	17-09-1996
US 6046922 A	04-04-2000	FR 2740630 A	30-04-1997
		EP 0772280 A	07-05-1997
		US 5781427 A	14-07-1998
JP 62233069 A	13-10-1987	JP 2911447 B	23-06-1999

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82